Meson spectra and m_T scaling in p+p, d+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

P. K. Khandai[1], P. Shukla[2,3],* and V. Singh[1]

[1]*Department of Physics, Banaras Hindu University, Varanasi 221005, India*

[2]*Nuclear Physics Division, Bhabha Atomic Research Center, Mumbai 400085, India and*

[3]*Homi Bhabha National Institute, Anushaktinagar, Mumbai 400094, India*

(Dated: October 19, 2011)

Abstract

The meson spectra provide insight into the particle production mechanism and interaction in the hadronic and quark gluon plasma (QGP) phases. The detailed study of systematics of meson spectra is important also because it acts as ingredient for estimating the hadronic decay backgrounds in the photon, single lepton and dilepton spectra which are the penetrating probes of quark gluon plasma. In this work, we parameterize experimentally measured pion spectra and then obtain the spectra of other light mesons using a property known as m_T scaling. The m_T scaled spectra for each meson is compared with experimental data for p+p, d+Au and Au+Au systems at $\sqrt{s_{NN}}$ = 200 GeV. The agreement of the m_T scaled and experimental data shapes are excellent in most cases and their fitted relative normalization gives ratio of meson to pion m_T spectra. These ratios are useful to obtain the hadronic decay contribution in photonic and leptonic channels but also point to the quantitative changes in the dynamics of the heavy ion collision over p+p collisions. It is shown that, the particles with charm contents behave differently as compared to pions in d+Au systems and particles either with strange or charm contents behave differently from pions in Au+Au systems. For Au+Au system, three centrality classes have been studied which reveal that for the particles like kaon and ϕ, peripheral collision data is better reproduced as compared to central and their relative ratios with pions also increase as the collisions become more central.

* pshukla@barc.gov.in

I. INTRODUCTION

Heavy ion collisions at relativistic energies are performed to create and study dense and/or hot matter in the laboratory. In Au+Au collisions at $\sqrt{s}_{NN} = 200$ GeV at RHIC, many signals point to the formation of Quark Gluon Plasma (QGP) [1]. At RHIC, currently detailed properties of the strongly interacting matter are under investigation using a variety of observables. To isolate phenomena related to the dense and hot medium created in such collisions and to understand cold nuclear matter effects, it is also important to measure particle production in smaller collision systems like p+p and d+A. Measurements of transverse momentum spectra for particles emerging from p+p collisions are used as a baseline to which similar measurements from heavy ion collisions are compared. In addition, several observations from p+p collisions, such as the p_T spectra with particle mass are interesting in their own right. The nuclear modification factor R_{AA} for several identified hadrons at high transfer momentum serve as a probe for jet quenching [2]. It has been observed that there is strong suppression of hadrons in Au+Au collisions while no suppression is observed in d+Au collisions [3]. The photons R_{AA} remains flat both for d+Au as well as for Au+Au collisions even at high p_T [4]. Being electromagnetic the photons escape unaffected and their spectra after subtracting the hadronic decay contribution reflect the properties of the medium such as temperature. The dielectron invariant mass measured by PHENIX collaboration shows enhancement over the cocktail from hadronic contribution in low mass region and is also associated to the thermal radiation from QGP [5]. The single electrons coming from semi electronic decays of charm and beauty quarks are important hard probes of the properties of matter produced in heavy ion collisions [6]. In order to obtain the electron spectra from charm decays one needs to subtract the electron contribution from other meson decays [7]. Getting the cocktail of single electrons, dielectrons and photon coming from the decays of all mesonic sources is crucial in any of the above analysis.

WA80 collaboration found that the spectral shapes of π and η mesons are identical when plotted as a function of m_T [8]. This property is known as m_T scaling and has been extremely useful to obtain the unknown meson spectra.

In this work, we used m_T scaling to obtain all mesonic spectra from a given meson spectrum. We parameterize pion spectra first and then we obtain the spectra of other light mesons using m_T scaling. The relative normalization of the m_T scaled spectra is then fitted

to the experimental data for all mesons in p+p, d+Au and Au+Au collisions. Both the magnitudes and shapes of the m_T scaled and experimental data are studied for all these systems for many particles namely K, η, ϕ, J/ψ and ω mesons.

II. FIT PROCEDURE USING m_T SCALING

In this section, we describe the fitting procedure using m_T scaling, but before that we give a brief theoretical background of the fit function used in our analysis. Hagedorn proposed the following imperical formula [9] to describe the data of invariant cross section of hadrons as a function of p_T over a wide range (0.3-10 GeV/c). Hagedorn described this as "inspired by QCD".

$$E\frac{d^3N}{dp^3} = \frac{A}{(1+\frac{p_T}{p_0})^n}. \tag{1}$$

Here A, p_0 and n are fit parameters. The two limiting cases of this formula are as follows:

$$\frac{1}{(1+\frac{p_T}{p_0})^n} \simeq \exp\left(\frac{-np_T}{p_0}\right), \quad \text{for } \ p_T \to 0 \tag{2}$$

$$\simeq \left(\frac{p_0}{p_T}\right)^n, \quad \text{for } \ p_T \to \infty. \tag{3}$$

At low transverse momenta it assumes an exponential form and at large transverse momenta it becomes a power law arises from "QCD inspired" quark interchange model [10] as:

$$E\frac{d^3N}{dp^3} \sim (m_T^2)^{-4} \sim \frac{1}{(p_T)^8} \tag{4}$$

Even though the inclusive cross section is dominated by low p_T particles, the hardening of the p_T distribution with increasing center of mass energy implies an increase of the transverse momentum. To better describe both low as well as high p_T range, UA1 collaboration [11] used a hybrid form as follows:

$$E\frac{d^3N}{dp^3} = B\exp(-bm_T), \ \text{ for } p_T < p_T^* \tag{5}$$

$$= \frac{A}{(1+\frac{p_T}{p_0})^n}, \quad \text{for } p_T > p_T^*. \tag{6}$$

with p_T^* as a free parameter. The PHENIX collaboration obtained a single form referred as modified Hagedorn formula [5, 12, 13]. The modification is to better describe the π^0 spectrum for wider p_T range, in particular at high p_T where the spectrum behaves close to a simple power law function. This single formula has been used to successfully describe the hadron spectra measured in p+p [5, 12–14], d+Au [14] as well as in Au+Au [5, 12, 14] collisions at different energies and is given by

$$E\frac{d^3N}{dp^3} = \frac{A}{\left[\exp(-ap_T - bp_T^2) + \frac{p_T}{p_0}\right]^n} \tag{7}$$

which is close to a Hagedorn function at low p_T and satisfies the requirement that the function is a pure power law at high p_T . The term quadratic in p_T in the exponential term in the denominator is more important for the Au+Au collisions.

In our analysis, first we parameterize experimentally measured pion spectra. In the fitting procedure, both neutral as well as charged pion data are incorporated. This is based on the assumption that the neutral pion spectrum is the same as the average charged pion spectrum. The fit function used here is the same modified Hagedorn distribution used by PHENIX collaboration but we replace p_T by m_T written as

$$\begin{aligned} E\frac{d^3N}{dp^3} &= \frac{A}{\left[\exp(-am_T - bm_T^2) + \frac{m_T}{p_0}\right]^n}, \\ &= f_\pi\left(\sqrt{p_T^2 + m_\pi^2}\right), \end{aligned} \tag{8}$$

where A, a, b, p_0 and n are the fit parameters. The pion spectra measured in p+p, d+Au and Au+Au systems are fitted using this distribution and the parameters obtained are given in table I. For Au+Au system, data corresponding to three centrality classes namely 0-20 %, 20-60 % and 60-92 % has been analyzed. The fit parameters for the centrality data for pions are given in table II. Comparing the values of b for different systems shows that term quadratic in m_T in the exponential term in the denominator is more important for the Au+Au collisions. We notice that the power n for all systems is close to 8 providing qualitative theoretical support for the quark interchange model.

The light mesons which contribute sizeably to any measured electron and/or photons via their decay are pions, η, ρ, ω, ϕ, $\eta\prime$ etc. The η meson contributes a sizeable fraction of decay

electrons, in particular at high p_T. Using m_T scaling, we obtain the spectra of these light neutral mesons using pion fit function as

$$E\frac{d^3N}{dp^3} = S\ f_\pi\left(\sqrt{p_T^2 + m_h^2}\right) \tag{9}$$

where m_h is the rest mass of the corresponding hadron or meson. The factor S is the relative normalization of the meson m_T spectrum to the pion m_T spectrum which we obtain by fitting the experimentally measured meson spectrum.

The factor S should be close to, but not identical to, some standard meson/π^0 ratios in the literature [15] that have been obtained as averaged over p_T intervals:

η/π^0=0.48 $\pm$ 0.03 [16];

ρ/π^0=1.0 $\pm$ 0.3, predicted by [17];

ω/π^0=0.9 $\pm$ 0.06 [18];

$\eta\prime/\pi^0$=0.40 $\pm$ 0.12, predicted by PYTHIA [17];

ϕ/π^0= 0.25 $\pm$ 0.08 [19];

These values are obtained mostly by p+p measurements and models for p+p collisions, but also are widely used in cocktail calculations for the d+Au system. For Au+Au system the ratios are given in Ref.[20]. All the meson data used in this analysis along with mode of measurement and p_T ranges with their references are listed in table III for p+p and in IV for d+Au and Au+Au systems. The particles like pions and kaons are measured by time of flight (TOF). The errors on the data are quadratic sums of statistical and uncorrelated systematic errors wherever available. All the data used in the present work is for same rapidity ($|y| < 0.35$) and from PNENIX experiment at RHIC.

III. RESULTS

Figure (1a) shows the invariant yields of neutral [21] and charged pions [22] as a function of m_T measured in p+p collision at $\sqrt{s_{NN}}$ = 200 GeV fitted with the Hagedorn function. The figure (1b) shows the ratio of data to the fit. Figure (2) shows the invariant yields of K$^\pm$ [22], η [16, 23], ϕ [13, 24] and J/ψ [25, 26] as a function of m_T measured in p+p system. The solid line is obtained using m_T scaling; the relative normalization has been used to fit

TABLE I. The parameters of the Hagedorn distribution obtained by fitting pion spectra measured in p+p, d+Au and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.

Parameters	Collision systems		
	p+p	d+Au	Au+Au
A (GeV/c)$^{-2}$	11.11 ± 0.37	52.30 ± 1.63	822.30 ± 15.90
a (GeV/c)$^{-1}$	0.32 ± 0.03	0.24 ± 0.01	0.420 ± 0.006
b (GeV/c)$^{-2}$	0.024 ± 0.011	0.11 ± 0.01	0.215 ± 0.006
p_0 (GeV/c)	0.72 ± 0.03	0.77 ± 0.02	0.697 ± 0.003
n	8.42 ± 0.12	8.46 ± 0.07	8.35 ± 0.01

TABLE II. The parameters of the Hagedorn distribution obtained by fitting pion spectra measured in Au+Au collisions of different centralities at $\sqrt{s_{NN}}$ = 200 GeV.

Parameters	Au+Au collision centrality		
	0-20 %	20-60 %	60-92 %
A (GeV/c)$^{-2}$	1883.23 ± 31.20	744.77 ± 9.11	132.99 ± 2.21
a (GeV/c)$^{-1}$	0.442 ± 0.006	0.385 ± 0.004	0.273 ± 0.005
b (GeV/c)$^{-2}$	0.242 ± 0.006	0.192 ± 0.004	0.154 ± 0.006
p_0 (GeV/c)	0.708 ± 0.003	0.694 ± 0.003	0.653 ± 0.006
n	8.40 ± 0.01	8.26 ± 0.01	8.14 ± 0.03

the measured spectra. Figure (3) shows the invariant yield of ω meson [13, 27] as a function of m_T measured in p+p system along with the m_T scaled curve (solid line).

Figure (4a) shows the invariant yields of neutral [28] and charged pions [22] as a function of m_T measured in d+Au at $\sqrt{s_{NN}}$ = 200 GeV fitted with the Hagedorn function. The figure (4b) shows the ratio of data to fit. Figure (5) shows the invariant yields of measured K$^{\pm}$ [22], η [16, 28], ϕ [24] and J/ψ [29] as a function of m_T measured in d+Au system. The solid line is obtained using m_T scaling; the relative normalization has been used to fit the measured spectra. Figure (6) shows the invariant yield of ω meson [27] as a function of m_T measured in d+Au system along with m_T scaled curve.

Figure (7a) shows the invariant yields of neutral [31] and charged pions [32] as a function of m_T measured in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV fitted with the Hagedorn function. The

TABLE III. Particles with their measured decay channels and p_T range for different p+p collisions with references. The data is for central rapidity region $|y| < 0.35$.

Particle	Mode	p_T range	Reference
π^0	$\gamma\gamma$	0.6-18.9 GeV	[21]
$\pi^\pm$	TOF	0.3-2.6 GeV	[22]
$K^\pm$	TOF	0.4-1.8 GeV	[22]
η	$\gamma\gamma$	2.7-11.0 GeV	[16]
		5.5-21 GeV	[23]
ϕ	e^+e^-	0-3.5 GeV	[13]
	K^+K^-	1-7.0 GeV	[24]
ω	e^+e^-	0.1-3.5 GeV	[13]
	$\pi^+\pi^-$	2.5-9.3 GeV	[27]
	$\pi^0\pi^+\pi^-$	2.25-13 GeV	[13]
J/ψ	e^+e^-	0.1-8.5 GeV	[25]
		0.1-8.5 GeV	[26]

figure (7b) shows the ratio of data to fit. Figure (8) shows the invariant yields of measured K$^\pm$ [32], η [23, 30], ϕ [24] and J/ψ [33] as a function of m_T in Au+Au system. The solid line is obtained using m_T scaling; the relative normalization has been used to fit the measured spectra.

Figure (9) shows the invariant yield of ω [34] meson as a function of m_T measured in Au+Au system along with m_T scaled curve.

The table V shows the normalization factor of meson to pion m_T spectra (meson/π^0) obtained by fitting the m_T scaled spectra with the measured spectra for different collision systems. In case of p+p they are in agreement with the ratios available in the literature. One can observe that the shapes of the derived m_T scaled spectra very well reproduce the measured spectra.

In case of d+Au, the fitted meson to pion ratios are in agreement with those in case of p+p for all mesons except for the J/ψ. The J/ψ to pion ratio is small in d+Au case because the J/ψ yields are suppressed but the pion yields remain unaffected. The shapes of the derived m_T scaled spectra reproduce all measured spectra including J/ψ. It shows that the

TABLE IV. Particles with their measured decay channels and p_T range for d+Au and Au+Au systems with references. The data is for central rapidity region $|y| < 0.35$.

Particle	Mode	p_T range	Reference
d+Au collision			
π^0	$\gamma\gamma$	1.2-17.0 GeV	[28]
$\pi^\pm$	TOF	0.3-2.6 GeV	[22]
$K^\pm$	TOF	0.45-1.8 GeV	[22]
η	$\gamma\gamma$	1.2-4.75 GeV	[16]
		2.25-11.0 GeV	[28]
ϕ	K^+K^-	1.1-7 GeV	[24]
ω	$\pi^0\gamma$	3-9 GeV	[27]
J/ψ	e^+e^-	0.5-4.5 GeV	[29]
Au +Au collision			
π^0	$\gamma\gamma$	1.2-19.0 GeV	[31]
$\pi^\pm$	TOF	0.25-2.95 GeV	[32]
$K^\pm$	TOF	0.45-1.95 GeV	[32]
η	$\gamma\gamma$	2.25-9.5 GeV	[30]
		5.5-21 GeV	[23]
ϕ	K^+K^-	1.1-7 GeV	[24]
ω	$\pi^0\gamma$	4.5-8.5 GeV	[34]
J/ψ	e^+e^-	0.25-5 GeV	[33]

J/ψ yields are suppressed uniformly in all the p_T range considered here.

In case of Au+Au, the fitted η to pion ratio is similar to that in case of pp. It is because η and pions are suppressed by similar amount. Also the shape of the curve matches well with the data. The same is true with ω. It means that one can obtain the ratios of the η and ω m_T spectra with pion m_T spectra for p+p collisions and then can use them for the case of d+Au and Au+Au systems. The kaon to pion ratio is larger than that in p+p and the m_T scaled curve does not reproduce the shape of the measured spectra that well. The ϕ to pion ratio is larger than that in p+p because the ϕ is not suppressed as much as pions. One can observe in case of ϕ that the shape of measured spectra is not well reproduced

TABLE V. The relative normalization (meson/π^0) obtained by fitting the m_T scaled spectra with the measured spectra for different collision systems.

	Collision systems		
particle ratio S	p+p	d+Au	Au+Au (MB)
K/π^0	0.422 ± 0.003	0.439 ± 0.002	0.530 ± 0.002
η/π^0	0.497 ± 0.015	0.460 ± 0.017	0.525 ± 0.040
ϕ/π^0	0.233 ± 0.011	0.215 ± 0.008	0.348 ± 0.017
ω/π^0	0.903 ± 0.021	0.964 ± 0.10	0.845 ± 0.145
J/ψ/π^0	0.054 ± 0.002	0.0021 ± 0.0002	0.0037 ± 0.0003

TABLE VI. The relative normalization (meson/π^0) obtained by fitting the m_T scaled spectra with the measured spectra for different Au+Au collision of different centralities.

	Au+Au collision			
particle ratio S	MB	0-20%	20-60%	60-92%
K/π^0	0.530 ± 0.002	0.504 ± 0.001	0.494 ± 0.001	0.486 ± 0.003
η/π^0	0.525 ± 0.040	0.542 ± 0.017	0.580 ± 0.014	0.548 ± 0.024
ϕ/π^0	0.348 ± 0.017	0.401 ± 0.010	0.391 ± 0.007	0.302 ± 0.014
	MB	0-20%	20-40%	40-92%
J/ψ/π^0	0.0037 ± 0.0003	0.0032 ± 0.0005	0.0043 ± 0.0005	0.0033 ± 0.0006

in intermediate m_T region of $m_T - m \sim 2$ to 4 GeV.. This shows that the particles with strangeness contents behave differently in Au+Au case.

The J/ψ to pion ratio is small in Au+Au case but even smaller in d+Au. This is quite interesting and is because the yield of pions is suppressed only in Au+Au but the yield of J/ψ is suppressed in both systems. Interestingly, the shape of the derived m_T scaled spectra reproduce the measured J/ψ spectrum. It shows that the J/ψ yields are suppressed uniformly in all the m_T range considered here.

We have also considered three centrality classes for Au+Au system; 0-20 % (most central), 20-60 % (intermediate) and 60-92 % (peripheral). In case of J/ψ we have data available for the centralities 0-20 %, 20-40 % and 40-92 %. The class 40-92 % in this case can be called as semiperipheral. Also we do not have good centrality data for ω. The table V shows the

normalization factor of meson to pion m_T spectra (meson/π^0) obtained by fitting the m_T scaled spectra with the measured spectra for different centralities.

Figure 10 shows the invariant yield of measured neutral [31] and charged pions [32] as a function of m_T in Au+Au system for different centralities. The solid lines are the Hagedorn function fits, the parameters of which are given in Table II. Figure 11 shows the invariant yield of measured $K^{\pm}$ [32] as a function of m_T in Au+Au system for different centralities. The solid lines are obtained using m_T scaling from the corresponding centrality data of pions. The relative normalization has been used to fit the measured spectra. Figure 12 shows the invariant yield of measured η (open symbols [30], solid symbols [23]) as a function of m_T in Au+Au system for different centralities. Figure 13 shows the invariant yield of measured ϕ [24] as a function of m_T in Au+Au system for different centralities. Figure 14 shows the invariant yield of measured J/ψ [33] as a function of m_T in Au+Au system for different centralities.

In case of η the data of all centralities are very well reproduced by m_T scaled pion data. The ratios obtained also remain approximately same. In case of kaons, the shapes of the peripheral data are reproduced by m_T scaled pion data very well but for the most central collisions the disagreement between the two is quite evident. Also the fitted ratios tend to increase as we move from peripheral to central collisions. The same seems true for ϕ where peripheral data is better reproduced as compared to central data and the ratios also increase as the collision becomes more central. In case of J/ψ all three centralities seem same both by shape and relative ratio to the pions. At least from the present data they can not be distinguished.

IV. CONCLUSION

In summary, we parameterize experimentally measured pion spectra and then obtain the spectra of other light mesons using a property known as m_T scaling. The m_T scaled spectra for each meson is compared with experimental data for p + p, d + Au and Au+Au systems at $\sqrt{s_{NN}}$ = 200 GeV. Their fitted relative normalization gives meson to pion ratio. These ratios would be useful to obtain the hadronic decay contribution in photonic and leptonic channels. The shape of the derived m_T scaled spectra very well reproduce the measured spectra and fitted meson to pions are in agreement with the ratios available in literature

for p+p system. We show that the ratios of the η and ω m_T spectra with pion m_T spectra obtained for p+p collisions can be used for the case of d+Au and Au+Au systems. It is observed that the particles with charm contents behave differently from pions for both the d+Au and Au+Au systems. The particles with strange contents behave similar as pions in d+Au system but behave differently from pions in Au+Au systems. The more detailed centrality analysis of Au+Au collision reveal that in case of η the data of all centralities are very well reproduced by m_T scaled pion data. The ratios obtained also remain approximately same. For particles, kaon and ϕ, peripheral data is better reproduced as compared to central data and the ratios also increase as the collision becomes more central. In case of J/ψ, all three centralities seems same both by shape and relative ratios to the pions within the errors.

V. ACKNOWLEDGEMENTS

We acknowledge the financial support from Board of Research in Nuclear Physics (BRNS) for this project.

[1] I. Arsene et. al. (BRAHMS), Nucl. Phys. A**757**, 1 (2005); B. B. Back et. al. (PHOBOS), Nucl. Phys. A**757**, 28 (2005); J. Adams et. al. (STAR), Nucl. Phys. A**757**, 10 (2005); K. Adcox et. al. (PHENIX), Nucl. Phys. A**757**, 184 (2005).

[2] K. Adcox et al. (PHENIX), Phys. Rev. Lett. **88**, 022301 (2001).

[3] S. S. Adler et al. (PHENIX), Phys. Rev. Lett. **94**, 082302 (2005).

[4] A. Adare et al. (PHENIX), Phys. Rev. Lett. **104**, 132301 (2010).

[5] A. Adare et al. (PHENIX), Phys. Rev. C**81**, 034911 (2010).

[6] M. L. Mangano et al., Nucl. Phys. B**405**, 507 (1993).

[7] A. Adare et al. (PHENIX), Phys. Rev. Lett. **98**, 172301 (2007).

[8] R. Albrecht et. al.(WA80 collaboration), Phys. Lett. B**361**, 14 (1995); arXiv:hep-ex/9507009.

[9] R. Hagedorn,Rev. del Nuovo Cim. **6N 10**, 1 (1984).

[10] R. Balnkenbecler and S.J. Brodsky, Phys. Rev. D**10**, 2973 (1974).

[11] C. Albajar et al. (UA1), Nucl. Phys. B**x** , 1 (1989).

[12] A. Adare et al. (PHENIX), arXiv:1005.1627(2010).

[13] A. Adare et al. (PHENIX), Phys. Rev. D**83**, 052004 (2011).

[14] S. Kelly (PHENIX), J. Phys. G**30** S1189 (2004).

[15] A. Adare et al. (PHENIX), Phys. Rev. Lett. **97**, 252002 (2006).

[16] S. S. Adler et al. (PHENIX), Phys. Rev. C**75**, 024909 (2007).

[17] T. Sjoestrand, S. Mrenna, and P. Skands, PYTHIA 6.4 physics and manual, JHEP 05, 026 (2006), arXiv:hep-ph/0603175.

[18] S. S. Adler et al. (PHENIX), Phys. Rev. C**75**, 051902 (2007).

[19] V. Ryabov et al., Nucl. Phys. A**774** 735 (2006).

[20] K. Adcox et al. (PHENIX), Phys. Rev. Lett **88**, 192303 (2002).

[21] A. Adare et al. (PHENIX), Phys. Rev. D**76**, 051106(R) (2007).

[22] S. S. Adler et al. (PHENIX), Phys. Rev. C**74**, 024904 (2006).

[23] A. Adare et al. (PHENIX), Phys. Rev. C**82**, 011902 (2010).

[24] A. Adare et al. (PHENIX), Phys. Rev. C**83**, 024909 (2011).

[25] A. Adare et al. (PHENIX), Phys. Rev. Lett. **98**, 232002 (2007).

[26] A. Adare et al. (PHENIX), Phys. Rev. D**82**, 012001 (2010).

[27] S. S. Adler et al. (PHENIX), Phys. Rev. C**75**, 051902 (2007).

[28] S. S. Adler et al. (PHENIX), Phys. Rev. Lett. **98**, 172302 (2007).

[29] S. S. Adler et al. (PHENIX), Phys. Rev. Lett. **96**, 012304 (2006).

[30] S. S. Adler et al. (PHENIX), Phys. Rev. Lett. **96**, 202301 (2006).

[31] A. Adare et al. (PHENIX), Phys. Rev. Lett. **101**, 232301 (2008).

[32] S. S. Adler et al. (PHENIX), Phys. Rev. C**69**, 034909 (2004).

[33] A. Adare et al. (PHENIX), Phys. Rev. Lett. **98**, 232301 (2007).

[34] A. Adare et al. (PHENIX), arXiv:1105.3467v1 (2011).

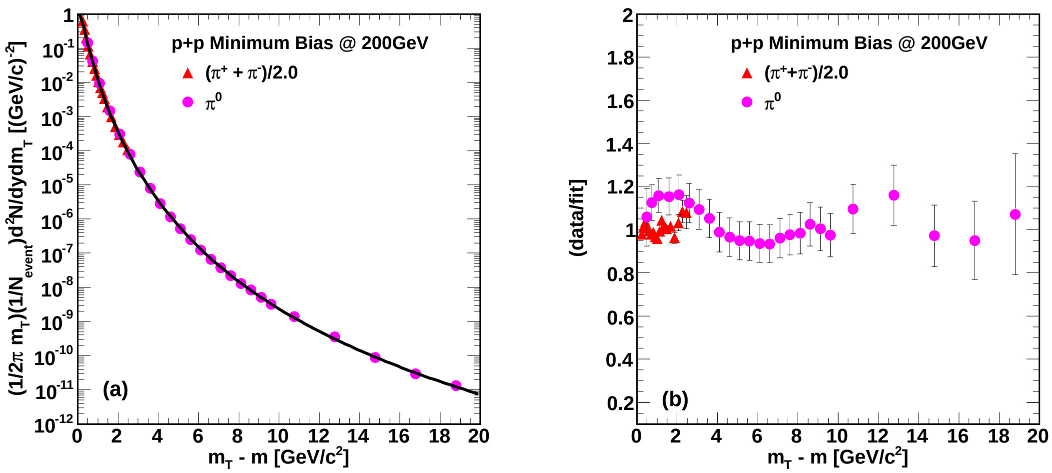

FIG. 1. (Color online) a) the invariant yields of neutral [21] and charged pions [22] as a function of m_T measured in p+p collision at 200 GeV fitted with the Hagedorn function. b) the ratio of data to the fit.

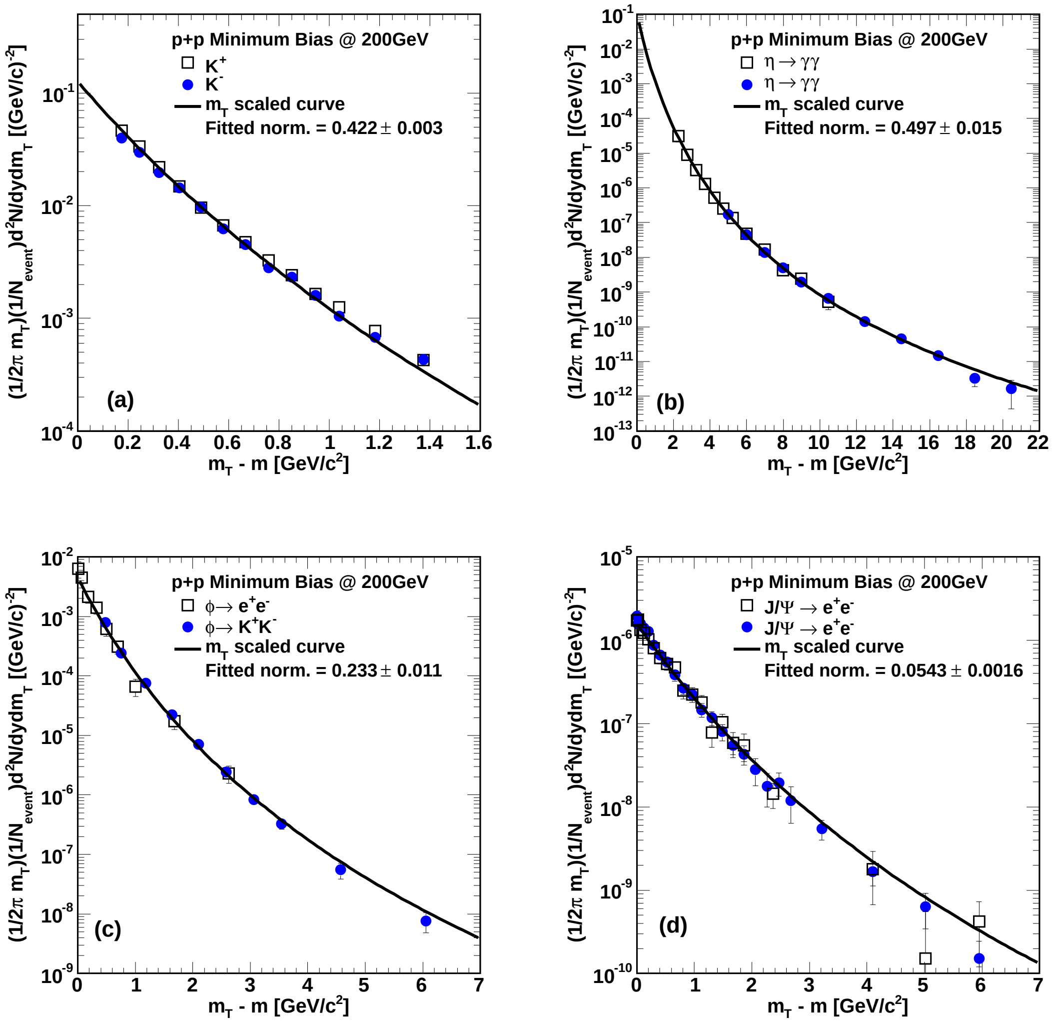

FIG. 2. (Color online) The invariant yield of K$^{\pm}$ [22], η (open squares [16], solid circles [23]), ϕ (open squares [13], solid circles [24]) and J/ψ (open squares [25], solid circles [26]) as a function of m_T measured in p+p system. The solid line is obtained using m_T scaling; the relative normalization has been used to fit the measured spectra.

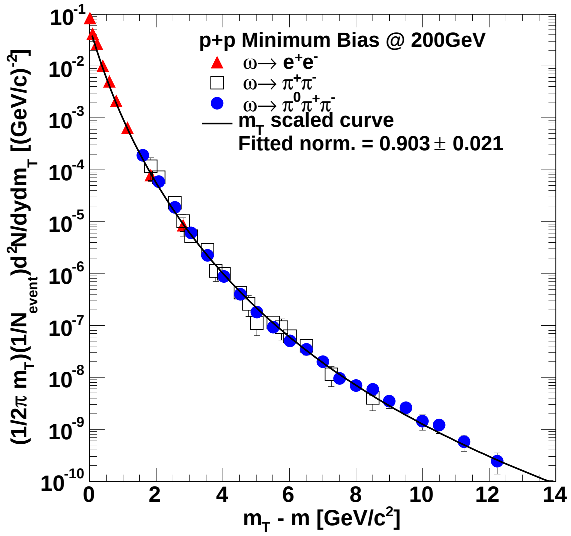

FIG. 3. (Color online) The invariant yield of ω meson (solid triangles [13], open squares [27], solid circles [13]) as a function of m_T measured in p+p system along with the m_T scaled curve (solid line).

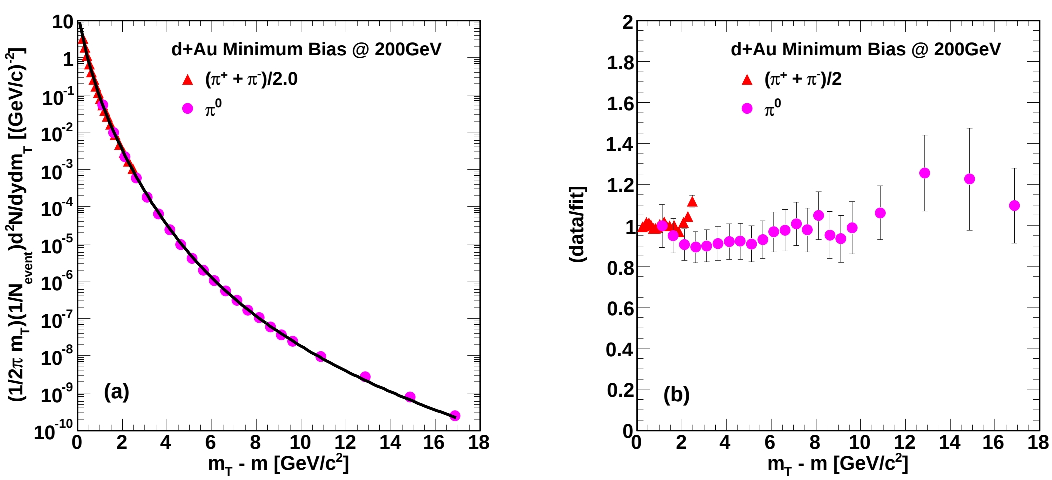

FIG. 4. (Color online) a) the invariant yields of neutral [28] and charged pions [22] as a function of m_T measured in d+Au at 200 GeV fitted with the Hagedorn function. b) the ratio of data to fit.

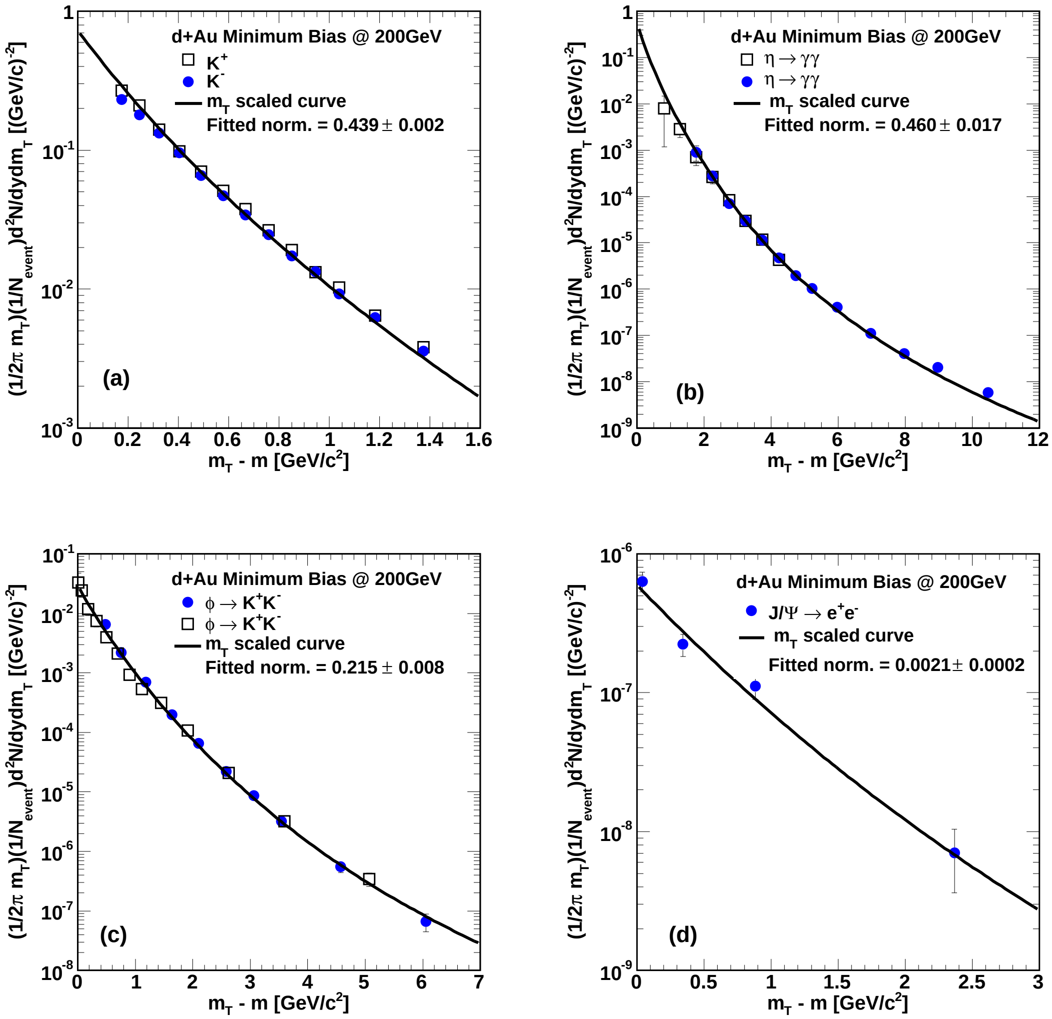

FIG. 5. (Color online) The invariant yield of measured K$^{\pm}$ [22], η (open squares [16], solid circles [28]), ϕ [24] and J/ψ [29] as a function of m_T measured in d+Au system. The solid line is obtained using m_T scaling; the relative normalization has been used to fit the measured spectra.

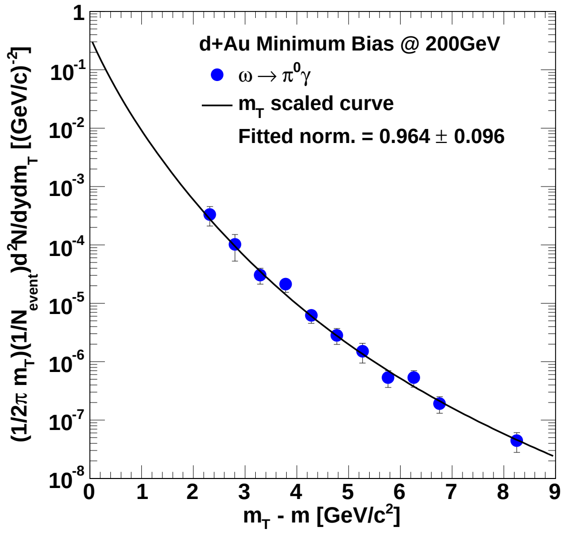

FIG. 6. (Color online) The invariant yield of ω [27] meson as a function of m_T measured in d+Au system along with m_T scaled curve.

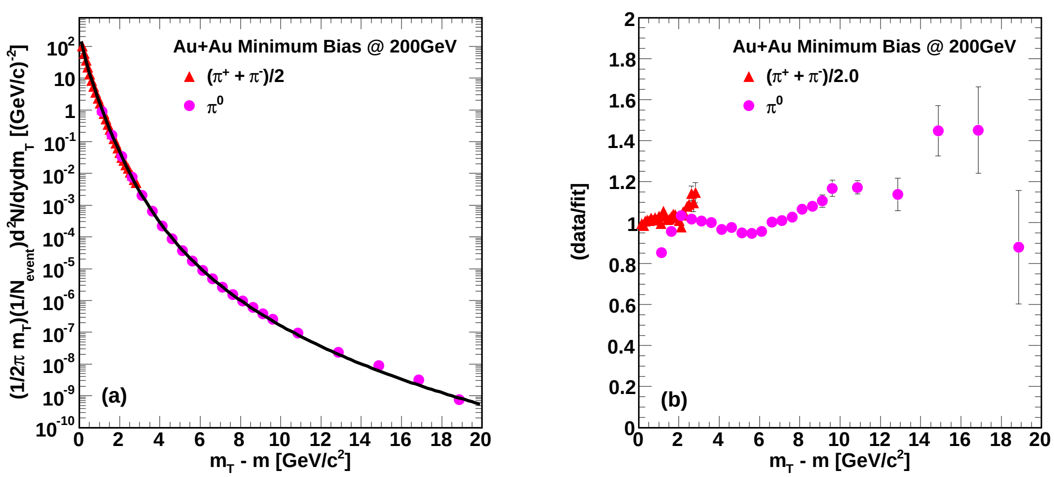

FIG. 7. (Color online) a) the invariant yields of neutral [31] and charged pions [32] as a function of m_T measured in Au+Au at 200 GeV fitted with the Hagedorn function. b) the ratio of data to fit.

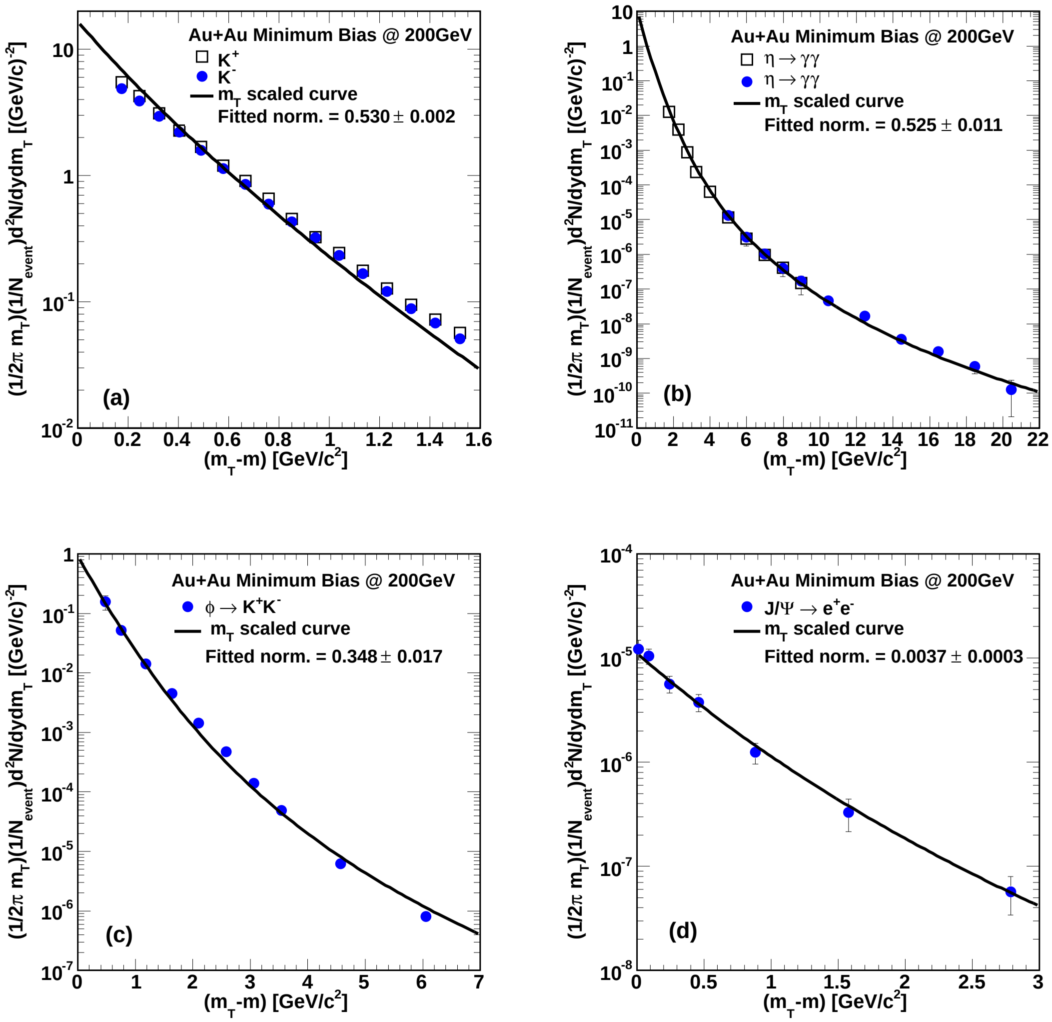

FIG. 8. (Color online) The invariant yield of measured $K^{\pm}$ [32], η (open squares [30], solid circles [23]), ϕ [24], J/ψ [33] as a function of m_T in Au+Au system. The solid line is obtained using m_T scaling; the relative normalization has been used to fit the measured spectra.

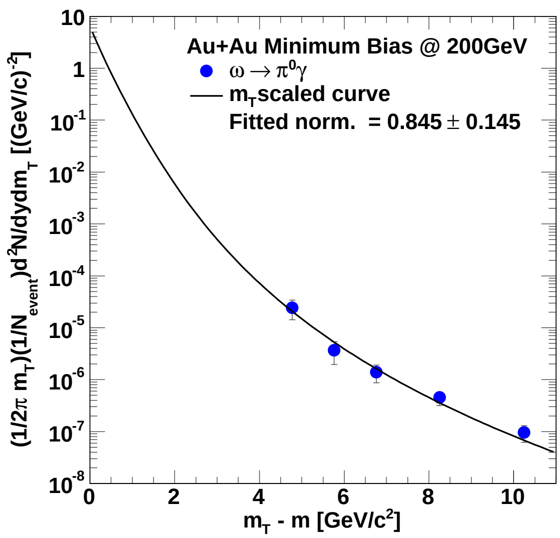

FIG. 9. (Color online) The invariant yield of ω [34] meson as a function of m_T measured in Au+Au system along with m_T scaled curve.

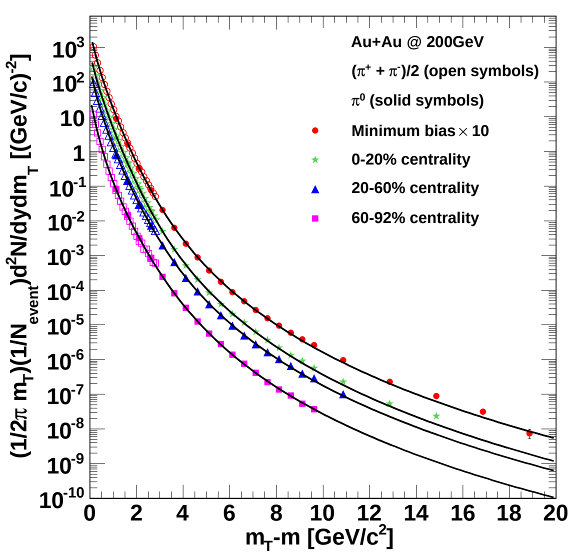

FIG. 10. (Color online) The invariant yield of measured neutral [31] and charged pions [32] as a function of m_T in Au+Au system for different centralities. The solid lines are the Hagedorn fit function.

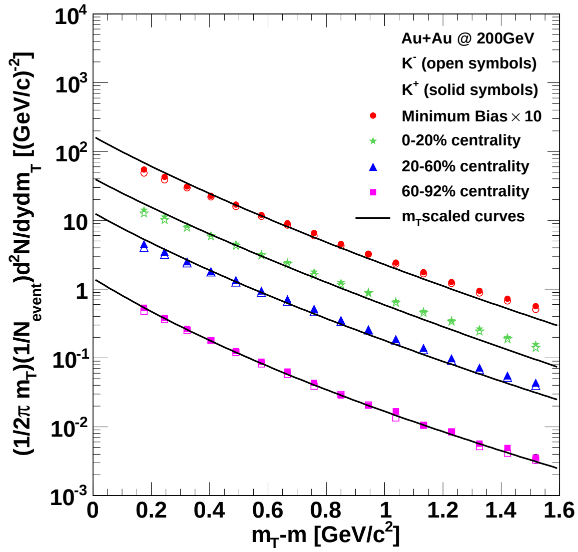

FIG. 11. (Color online) The invariant yield of measured K$^{\pm}$ [32] as a function of m_T in Au+Au system for different centralities. The solid lines are obtained using m_T scaling; the relative normalization has been used to fit the measured spectra.

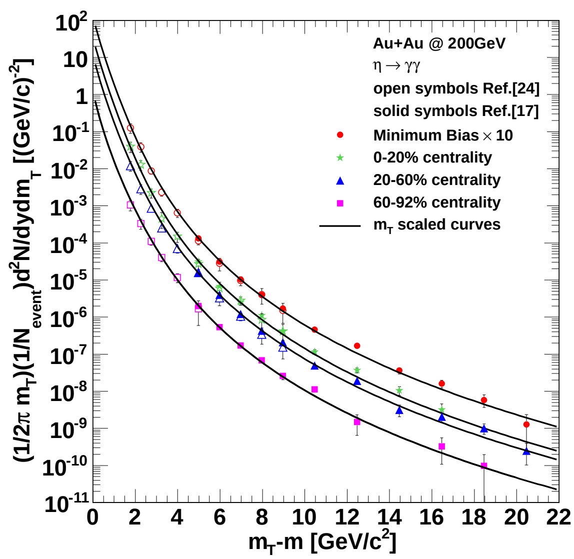

FIG. 12. (Color online) The invariant yield of measured η (open squares [30], solid circles [23]) as a function of m_T in Au+Au system for different centralities. The solid lines are obtained using m_T scaling; the relative normalization has been used to fit the measured spectra.

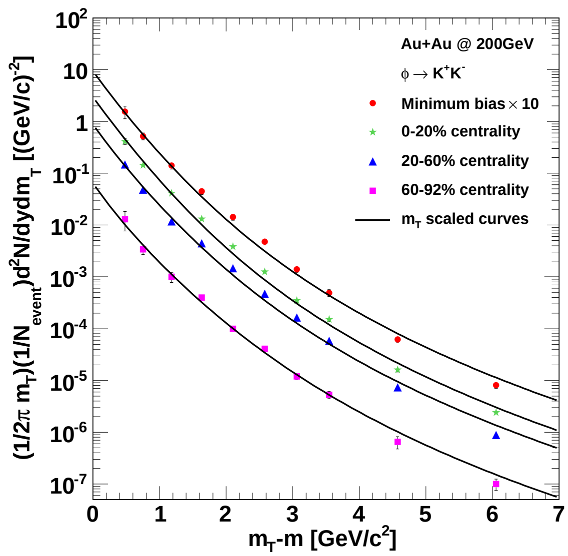

FIG. 13. (Color online) The invariant yield of measured ϕ [24] as a function of m_T in Au+Au system for different centralities. The solid lines are obtained using m_T scaling; the relative normalization has been used to fit the measured spectra.

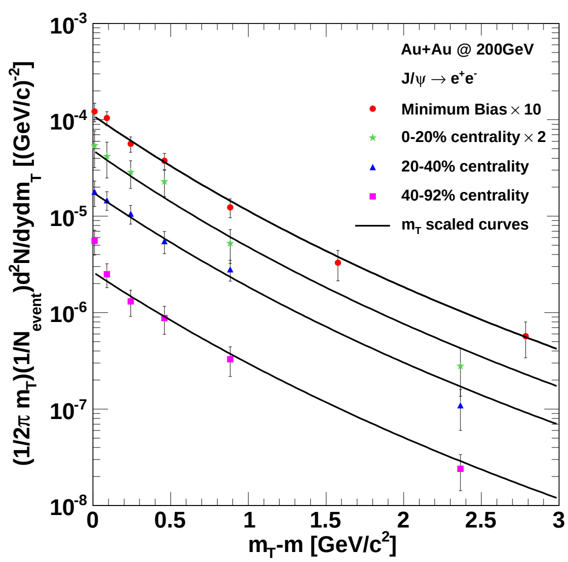

FIG. 14. (Color online) The invariant yield of measured J/ψ [33] as a function of m_T in Au+Au system for different centralities. The solid lines are obtained using m_T scaling; the relative normalization has been used to fit the measured spectra.